ISSN 2320-9984

Volume 12 Issue 3 | September 2024 ISSN: 2320-9984 (Online)

International Journal of Modern Engineering & Management Research

Website: www.ijmemr.org

Performance Optimization of Solar Water Heating Systems in Different Climates

Vishal Singh
Research Scholar M.Tech.
Thermal System and Design
Guru Ramdas Khalsa Institute of Technology
Jabalpur (M.P.), India
Email: vishaltech1995@gmail.com

Vishwajeet Kureel
Assistant Professor
Department of Mechanical Engineering
Guru Ramdas Khalsa Institute of Technology
Jabalpur (M.P.), India
Email: y2kvishwajeet@gmail.com

Abstract—*Solar energy can be utilized as a form of heat, such as solar water heating and as electricity, such as solar photovoltaic. Solar water heating systems are commonly referred to in industry as Solar Domestic Hot Water (SDHW) systems and it is a technology that is not entirely new. In the theoretical and practical investigations that the performance of solar water heater very much depends upon the solar radiation incident on the collector surface. Therefore it is very important to monitor the nature of variation of solar intensity throughout the day. Also it is important to study the variation of average temperatures daily throughout a month, so that we can predict the practical usefulness of a solar water heating system in the Indian scenario.*

Keyword :— *fossil fuels, Solar Domestic Hot Water (SDHW), GWth (gigawatt thermal), Coefficient of Performance (COP), Solar-Assisted Heat Pump (SAHP)*

1. INTRODUCTION

The need for renewable energy has been recognized globally as population and the demand for fossil fuels increase. The depleting resources of fossil fuels and increased costs have led to the development of new and technologically advanced renewable energy sources. With the government committed to increase the use of renewable sources of energy, they will slowly replace the use of some fossil fuels. The country as a whole is over reliant on imported gas, coal and oil. Solar water heating production has become more appealing in recent years on a global level; however it has been less popular in India to date on commercial projects. With the over reliance on fossil fuels for energy production, the Indian Government have realized the need to research and develop this area further. With India's dependency on fossil fuel in mind, solar water heating, where water is heated directly from the energy of the sun is becoming an increasingly attractive option.

The amount of solar thermal projects installed grew by 9% around the world in 2017. The total output worldwide reached 88,845 GWh, which resulted in the prevention of 39.3 million tons of CO_2 emissions escaping into the atmosphere. Statistics at the end of 2010 indicated that the total solar thermal collector capacity in operation worldwide was 195.8 GWth (gigawatt thermal), which equaled to 279.7 million m^2 of collectors. At the end of 2011 the capacity had increased by 25%, to 245 GWth. Making up this installed capacity, 88.3% comprised of flat-plate collectors and evacuated tube collectors, 11% unglazed water collectors and 0.7% air collectors. China accounts for the majority of glazed and unglazed water and air collectors in operation with 117.6 GWth, Europe accounts for 36.0 GWth and the United States & Canada has 16.0 GWth, which are mostly unglazed collectors. All of these countries and continents together account for 86.6% of total installed capacity in the world [37].

World solar water heating capacity has increased four times since 2000, writes Leonardo Energy. The growth is closely linked to promotion policies. Water heating represents about 15 percent of household's energy uses in Europe, 20 percent in the United States and even 30 percent in Japan. On one side, countries with a long-term promotion policy have a high share of systems installed per capita (Austria, Germany, Turkey, etc.) and in some cases reaching saturation (Cyprus and Israel). On the other side, a new market for solar water heaters is developing for many countries, in particular in emerging countries, such as China and Brazil. China ranks first in terms of installed capacity, with almost two thirds of the world's capacity. Cyprus is the world leader in terms of capacity per capita - followed by Israel, due to high solar radiation and support policies [30].

According to preliminary estimates, the SWH market is estimated to have risen to about 185 GWth in 2020, of which 70% of new capacities were installed in China and 10% in the European Union. The European market for SWH contracted again in 2020, by almost 13% after a 10% drop in 2019 due to the global economic crisis (slowdown in construction in countries with legislative promotion such as Spain or Greece, stop-and-go policy in Germany and the Czech Republic for subsidies, preference for solar PV incentives in France, etc.). In the European Union, the development of SWH systems is included in the National Renewable Energy Action Plans by member states and most of European countries have set targets for solar heat by 2025 [30].

The figure below shows the worldwide distribution of installed solar water heater capacity in 2023 [30]. As is evident form the figure India has only 1 % of the total installed capacity. Hence Indian government has taken major steps to excel in this new area of energy source.

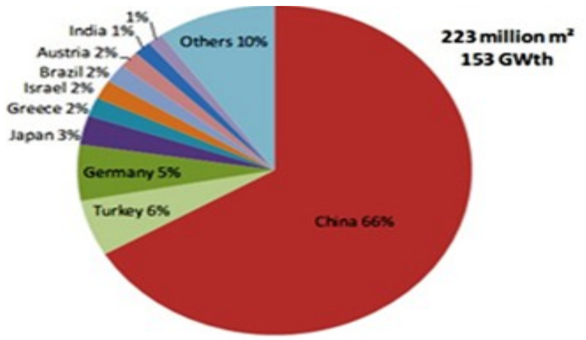

Figure 1: Distribution of Installed Solar Water Heater Capacity in 2023 [30],[34]

2. SOLAR WATER HEATERS

2.1 Overview of Solar Water Heating:

Solar energy can be utilized as a form of heat, such as solar water heating and as electricity, such as solar photovoltaic. Solar water heating systems are commonly referred to in industry as Solar Domestic Hot Water (SDHW) systems and it is a technology that is not entirely new. In the 19^{th} century, people used a stove to heat water by burning pieces of wood or coal. In cities, people heated their water with gas manufactured from coal. In many areas, wood, coal or gas could not be easily obtained and hence such fuels were often expensive [42]. To avoid these problems, a much easier and safer way to heat water was created. This was achieved by placing outside a black painted metal tank full of water to absorb solar energy. The disadvantage was that even on clear hot days it usually took from morning to early afternoon for the water to get hot. As the sun went down, the tank rapidly lost its heat because it had no insulation [42].

2.2 Types of Solar Water Heating Systems:

These systems can be classified into three main categories [1]: Active Systems, Passive Systems and Batch Systems.

2.2.1 Active Systems:

Active systems use electric pumps, valves, and controllers to circulate water or other heat-transfer fluids through the collectors. So, the Active systems are also called forced circulation systems and can be direct or indirect. The active system is further divided into two categories:

- Open-loop (Direct) Active System
- Closed-loop (Indirect) Active System

(a) Open-Loop Active Systems: Open-loop active systems as shown in Figure 2 use pumps to circulate water through the collectors. This design is efficient and lowers operating costs but is not appropriate if the water is hard or acidic because scale and corrosion quickly disable the system. These open-loop systems are popular in non-freezing climates.

(b) Closed-Loop Active Systems: These systems pump heat-transfer fluids (usually a glycol-water antifreeze mixture) through collectors as shown in Figure 3. Heat exchangers transfer the heat from the fluid to the household water stored in the tanks. Closed-loop glycol systems are popular in areas subject to extended freezing temperatures because they offer good freeze protection.

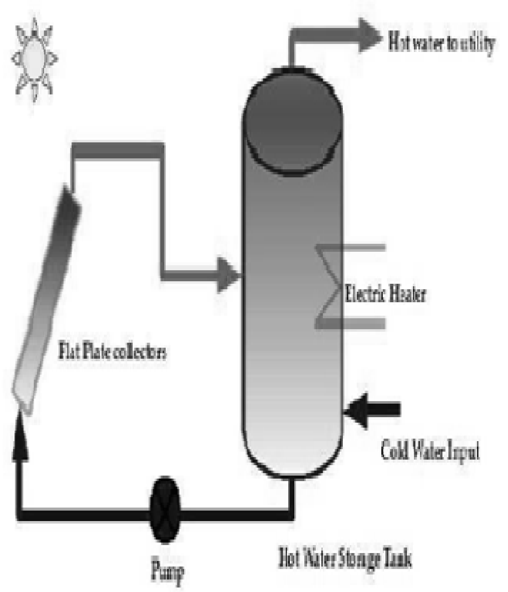

Figure 2: Open Loop Active System [1]

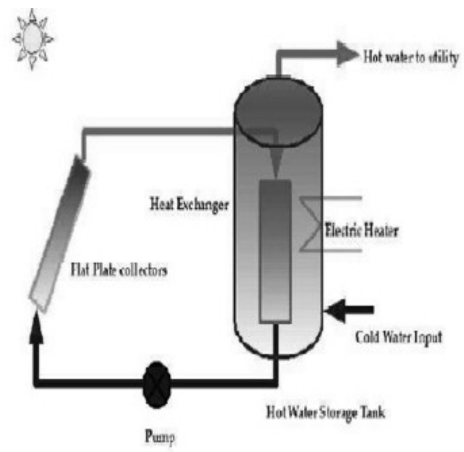

Figure 3: Closed Loop Active System [1]

2.3 Components of Solar Water Heating System:

A solar water heating system consists of several key components that work together to capture solar energy and convert it into thermal energy for heating water. Here’s an overview of the main components:

1. Solar Collector

Function: The solar collector is responsible for capturing solar energy and transferring it to the water or heat transfer fluid.

Types:

- ***Flat Plate Collectors:*** Commonly used, these have an absorber plate that absorbs sunlight and heats the fluid inside.
- ***Evacuated Tube Collectors:*** More efficient in colder climates, these consist of vacuum-sealed tubes that reduce heat loss.

2. Heat Transfer Fluid (HTF)

Function: The HTF circulates between the solar collector and the heat exchanger to transfer the absorbed solar energy. It can be water or a mixture of water and antifreeze.

Role: In indirect systems, the fluid is heated by the collector and used to transfer heat to the water in the storage tank via a heat exchanger.

3. Heat Exchanger

Function: The heat exchanger transfers heat from the solar collector to the water in the storage tank without mixing the fluids. This is common in indirect systems that use a separate heat transfer fluid.

Types: Coil heat exchangers or plate heat exchangers are commonly used.

4. Storage Tank

Function: The storage tank holds the heated water until it is needed. It is typically well-insulated to reduce heat loss.

Types:

- **Direct Storage:** The water heated in the collector is directly stored.
- **Indirect Storage:** Water is heated via a heat exchanger, with the heat transfer fluid circulating separately.

5. ***Circulation Pump (for Active Systems)***

Function: In active systems, the circulation pump moves the heat transfer fluid or water between the solar collector and the storage tank.

Role: Ensures continuous heat transfer, especially in larger systems or those that require enhanced control.

6. Controller

Function: The controller regulates the system's operation, ensuring that the circulation pump only operates when there is sufficient solar energy available (i.e., when the collector is warmer than the storage tank).

Role: It improves efficiency by preventing unnecessary energy consumption.

7. Expansion Tank

Function: The expansion tank allows for the expansion of the heat transfer fluid when it is heated. This prevents excessive pressure buildup in the system.

Role: Ensures system safety and longevity.

8. Temperature Sensors

Function: These sensors monitor the temperature of the collector, heat exchanger, and storage tank, feeding data to the controller.

Role: Used to optimize the system's performance and prevent overheating.

9. Auxiliary Heater (Optional)

Function: When solar energy is insufficient (e.g., during cloudy weather or nighttime), an auxiliary heater, such as an electric or gas heater, can be used to supplement the system.

Role: Ensures a reliable supply of hot water regardless of solar conditions.

10. Piping and Insulation

Function: The piping carries the heat transfer fluid between components, and the insulation minimizes heat loss.

Role: Proper insulation of pipes is crucial for maintaining system efficiency.

11. Check Valves and Pressure Relief Valves

Function: Check valves prevent reverse flow of fluids, while pressure relief valves release excess pressure to protect the system.

Role: Ensure system safety and prevent damage from overpressure.

These components work together to efficiently collect, store, and distribute solar energy for water heating applications in both residential and commercial settings.

3. DESIGN METHODOLOGY

The solar water heater system designed here is based upon the concept of absorbing maximum solar radiation from the sun and transferring it to the water flowing through the riser tubes. It utilizes a flat plate collector system made up of glass and aluminum riser tubes for absorbing the solar radiation. Maximum effort has been made to make the collector most efficient without increasing the cost. The setup is inclined at 23° to get maximum solar radiation with respect to location of Jabalpur, India.

In order to evaluate the solar water heater thermal efficiency, we must know its mathematical background.

3.1 Collector thermal efficiency (η) Calculation:

The efficiency of a solar collector is the ratio of the amount of useful heat collected to the total amount of solar radiation striking the collector surface during any period of time:

Solar energy collectedQu

η = ---

= ---------

Total solar striking collector surface

$$I \times Ac$$

The equation for mass flow rate (m) is:

$$m = \rho \times Q$$

where ρ is the density of water, which depends on the temperature and Q is the volume flow rate, which depends on the pressure difference at the orifice, which is measured from the inclined tube manometer and temperature.

Useful heat collected for solar collector can be expressed as:

$$Qu = mC_p\,(Tout - Tin)$$

where C_p is the specific heat of water and A_c is the area of the collector. The fractional uncertainty about the efficiency from the above equation is a function of ΔT, m˙, and I, considering C_p and A_c as constants. With

$$m = Vf \cdot S$$

So, collector thermal efficiency becomes:

$$\eta = mC \frac{(Tout - Tin)}{I\ Ac}$$

Where,

- T_{in} is the temperature of inlet (ºC)
- T_{out} is the outlet fluid temperature (ºC)
- Cp is the specific heat of water (J/kg K)
- A_c area of absorber plate surface (m^2)
- ΔT is the temperature difference (ºC)
- V_f is the water velocity (m/s)
- S is the passage cross section area (m^2)
- Q_u is the useful heat collected for an air-type solar collector (W)
- Q is the volume flow rate (m^3/s)
- I is the global irradiance incident on solar water heater collector (W/m^2)

In the above calculation we have not considered the heat loss from collector surface to the surroundings and have ignored it.

Some general guidelines can be followed while carrying out experiment on the setup to get best results:

- System installed in high windy area should be well grouted/ clamped with collectors installed in a way that it is able to sustain the highest wind pressure of that area.
- All the collectors will be south facing inclined at suitable angle to give best performance in winter.
- There should not be any shadow falling on the collectors from nearby structures or of other collectors in front or back row.
- Hot water pipe lines of any kind in

colder regions will be fully insulated from the point of withdrawal of water from tank to delivery points. In other regions also care should be taken to avoid heat losses from pipelines.

- System will be installed nearest to the point of hot water usage to avoid longer pipeline & higher heat losses.
- Where water quality is bad, care should be taken to avoid corrosion of pipes.
- The workmanship & aesthetics of the system will be good and it should be visible to anybody.
- Air vent pipe, make up water and cold water tanks will be installed as required for smooth functioning of the system.
- There should not be any leakage observed in the system from tanks/ collectors/ pipelines.

4. SOLAR WATER HEATING (SWH) IN DIFFERENT CLIMATES

Solar water heating (SWH) systems are used worldwide and perform differently depending on the climate. These systems rely on sunlight to heat water, which means that climate conditions—sunlight availability, temperature variations, and weather patterns—play a crucial role in determining the design and efficiency of the system. Here's a breakdown of how SWH systems function in different climates:

1. Tropical and Hot Climates

- ***Countries***: India, Brazil, Indonesia, etc.
- ***Characteristics***: Abundant sunlight, warm temperatures, minimal temperature variation.
- ***Best Systems***: ***Direct or open-loop systems*** are common, where water circulates directly through the collectors and is heated by the sun. There's minimal risk of freezing, so anti-freeze or indirect systems are unnecessary.
- ***Efficiency***: Very high efficiency due to consistent and strong solar radiation.

Considerations: These systems often need backup for cloudy or rainy periods, and over-sizing the system can lead to overheating in peak summer months.

2. Temperate Climates

- ***Countries***: Parts of Europe, North America, Australia.
- ***Characteristics***: Mild temperatures, seasonal variation in sunlight.
- ***Best Systems***: ***Indirect or closed-loop systems*** are common. These use a heat exchanger with a fluid (often anti-freeze) circulating through the collector and transferring heat to the water.
- ***Efficiency***: Moderate to high during spring and summer, but drops in winter due to reduced sunlight.

Considerations: Some backup heating (such as electric or gas) is usually needed for winter months. Systems need to be sized to ensure sufficient heating even in colder months.

3. Cold and Snowy Climates

- ***Countries***: Northern Europe (Scandinavia), Canada, Russia.
- ***Characteristics***: Cold temperatures, snow, and ice, significant seasonal variation in sunlight.
- ***Best Systems***: ***Evacuated tube collectors*** are more efficient in cold climates due to their superior insulation. Closed-loop systems using a heat exchanger with anti-freeze fluid are also necessary to prevent freezing.
- ***Efficiency***: Lower efficiency during

the winter months due to reduced sunlight and snow covering the panels. However, evacuated tubes can still generate heat from diffuse sunlight.

Considerations: These systems require additional heating sources for extremely cold periods. Regular maintenance is needed to clear snow from collectors.

4. Desert Climates

- ***Countries:*** Middle East, parts of Africa, Southwest US.
- ***Characteristics:*** Extremely high temperatures, clear skies, and intense solar radiation.
- ***Best Systems:*** ***Direct or open-loop systems*** are highly effective due to intense solar radiation, though care must be taken to avoid overheating during the hottest months.
- ***Efficiency:*** Very high efficiency, but the system must be carefully sized to handle high solar gains.

Considerations: In extremely dry regions, dust accumulation on collectors can reduce efficiency, so regular cleaning is essential.

5. Cloudy and High-Rainfall Climates

- ***Countries:*** UK, Pacific Northwest (US), Japan.
- ***Characteristics:*** Frequent cloud cover, high rainfall, and lower levels of sunlight.
- ***Best Systems:*** ***Evacuated tube collectors*** are often preferred, as they can still function effectively in diffuse light conditions. Indirect systems are common to deal with cooler temperatures.
- ***Efficiency:*** Moderate to low, depending on the season. Backup heating systems (e.g., gas or electric) are often required.

Considerations: These regions may require larger systems or more collectors to compensate for less direct sunlight.

6. Mountainous or High-Altitude Climates

- ***Countries***: Nepal, Andes region, Rocky Mountains.
- ***Characteristics***: Cool temperatures but strong solar radiation due to the thinner atmosphere.
- ***Best Systems***: **Evacuated tube collectors** or **high-efficiency flat-plate collectors** are suitable. Closed-loop systems with anti-freeze fluid prevent freezing in cold nights and winters.
- ***Efficiency***: High, as sunlight is intense even with colder air temperatures.

Considerations: Freeze protection is crucial, and snow buildup needs to be cleared from the collectors.

Key Takeaways:

- Hot climates favor direct systems due to no risk of freezing.
- ***Cold climates*** require **closed-loop systems** with anti-freeze and **evacuated tubes** for better insulation.
- ***Temperate climates*** *benefit from* ***indirect systems*** with seasonal variations in efficiency.
- ***Desert regions*** require regular cleaning of panels to ensure high efficiency.
- ***Mountainous areas*** benefit from strong sunlight but need freeze protection systems.

By choosing the appropriate SWH system for your climate, you can ensure optimal performance year-round.

4. FUTURE SCOPE

Although the designed setup proved to be quite efficient but still further improvements can be made to improve the performance. The present setup can be modified in a number of ways to increase its efficiency as discussed in the chapter on literature survey based on the advanced research in this field, but keeping in view the cost aspects. The collector design can be modified in number of ways to increase the efficiency. Better insulating materials can be provided to avoid heat loss to the surroundings. The sizing of the whole setup can be done. The variable mass flow rate, heat loss to the surroundings etc. can be measured as well to see their effects on the performance of the system.

Also, the electrical energy savings can be calculated to find out the actual financial savings with some light thrown on the economic aspects of solar thermal water heaters such as life-cycle cost calculations and electrical energy tariffs. Furthermore, the system reliability improvement with the introduction of solar thermal water heaters in a residential distribution circuit can be analyzed.

Extending the work covered in this thesis, improvements and modifications could be made in the experimental test rig in order to further enhance the efficiency of the setup. The following improvements could be performed:

The proposed future research will improve existing knowledge on solar collectors and enhance their performance, without increasing the cost much.

Reduction of heat losses from the system by using more advance thermal insulation of all components of the system.

Use of insulated storage tank for the collector to minimize the heat loss to the atmosphere.

5. CONCLUSION

The performance optimization of solar water heating systems across different climates presents a promising opportunity for enhancing energy efficiency and reducing carbon footprints. By integrating solar energy with advanced heat pump technology, these systems can provide reliable and sustainable water heating solutions, even in varying environmental conditions. The effectiveness of a solar-assisted heat pump system largely depends on several factors, including the solar collector type, heat pump capacity, storage tank size, and the implementation of advanced control strategies.

This research demonstrates that optimizing system design and operation can significantly improve the coefficient of performance (COP), increase energy savings, and maximize the solar fraction, even in regions with limited solar insolation. In warmer climates, larger solar collectors and advanced controls can be leveraged to fully utilize available solar energy, while in colder climates, evacuated tube collectors and optimized heat pump operation can maintain efficiency. Seasonal variations, climatic conditions, and energy demands must be carefully analyzed to tailor systems for specific applications.

The study emphasizes the importance of selecting appropriate components and optimizing operational strategies for different climates to ensure high performance and cost-effectiveness. Future research should explore the integration of smart grid technologies, predictive algorithms, and hybrid energy systems to further enhance the flexibility and adaptability of solar water heating systems.

In conclusion, with proper optimization, solar water heating systems offer a highly efficient, eco-friendly, and cost-effective solution for meeting global water heating demands while supporting the transition to a more sustainable energy future.

REFERENCES:

[1] Kishan Patel, Pragna Patel, Jatin Patel; "Review of solar water heating systems", International Journal of Advanced Engineering Technology, E-ISSN 0976-3945, Vol.III/ Issue IV/ Oct.-Dec., 2012/146-149

[2] P. Sivakumar, W. Christraj, M. Sridharan, N. Jayamalathi; "Performance improvement study of solar water heating system", ARPN Journal of Engineering and Applied Sciences, Volume 7, Issue 1, . 2012, Pages 45-49.

[3] N.M. Nahar "Year round performance and potential of a natural circulation type of solar water heater in India", Energy and Buildings, Volume 35, Issue 3, March 2003, Pages 239-247

[4] Foued Chabane, Noureddine Moummi, Said Benramache; "Experimental study of heat transfer and thermal performance with longitudinal fins of solar air heater", Journal of Advanced Research, Volume 5 Issue 2 2014, Pages 183-192

[5] Bukola Olalekan Bolaji, "Flow design and collector performance of a natural circulation solar water heater". Journal of Engineering and Applied Sciences. Volume 1, Issue 1, 2006, Pages 7-13

[6] V.R. Bhore, S.B. Thombre; "A Simple Method for indoor and outdoor testing of a flat plate collector operating under natural circulation mode", proceedings, international conference on recent advance in solar energy conversation systems, MANIT, Bhopal, 2002.

[7] Govind Singh Chouhan, Ram Kumar Agarwal; "Experimental analysis of a batch type solar water heater with intregrated collector water storage system", International Journal of Emerging Technology and Advanced Engineering, Volume 3, Issue 5, May 2013, Pages 269-274

[8] L.M. Ayompe, A. Duffy; "Analysis of the Thermal Performance of a Solar Water Heating System with Flat Plate Collectors in a Temperate Climate", Applied Thermal Engineering, Volume 58, Issues 1–2, September 2013, Pages 447-454

[9] Y.Y. Nandurkar, R.S. Shelke; "Review of performance and analysis of ISI flat plate collector with modified flat plate collector", International Journal of Engineering Science and technology, Volume 4 Issue 4, 2012, Pages 944-946

[10] Abdollah Riahi, Hessam Taherian; "Experimental investigation on the performance of thermosyphon solar water heater in the south caspian sea", Thermal Science Volume 15, Issue 2, 2011, Pages: 447-456 https://doi.org/10.2298/TSCI1102447R